SELF-SHIELDED GRADIENT FIELD COIL FOR MAGNETIC RESONANCE IMAGING

The following relates to the diagnostic imaging arts. It particularly relates to magnetic field gradient coils for use in short-bore magnetic resonance imaging scanners, and will be described with particular reference thereto. However, the

5   following relates more generally to magnetic field gradient coils for various types of magnetic resonance imaging scanners, and to dedicated gradient coils for imaging reduced volumes of interest.

In a magnetic resonance imaging system, spatial

10   encoding of the magnetic resonances is typically accomplished by generating magnetic field gradients in an imaging region. These gradients are produced by a set of magnetic field gradient coils. Gradient coils are typically provided for producing independent magnetic field gradients in each of the

15   transverse x- and y-directions, and in the axial z-direction.

For various applications, such as producing gradients in short-bore magnetic resonance imaging scanners, or producing dedicated localized gradients over a reduced field of view (FoV) for imaging specific organs, it is desirable to employ

20   relatively shorter gradient coils. In scaling gradient coils to reduced length while retaining high gradient peak amplitudes and linearity and bore diameter, coil turns become increasingly compressed near the coil extremities. Moreover, imaging distortions and artifacts due to eddy currents induced in a

25   surrounding cold shield become more problematic. Furthermore, adaptive or variable field of view gradient coils are desired to adapt a given magnetic resonance scanner or magnetic field gradient coil set for a wider range of applications.

The present invention contemplates an improved

30   apparatus and method that overcomes the aforementioned limitations and others.

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According to one aspect, a gradient coil is disclosed for a magnetic resonance imaging apparatus. A primary coil defines an inner cylindrical surface. A shield coil defines an outer cylindrical surface coaxially aligned with the inner cylindrical surface and having a larger cylindrical radius than the inner cylindrical surface. A plurality of coil jumps electrically connect the primary and shield coils. The coil jumps define a non-planar current-sharing surface extending between an inner contour coinciding with the inner cylindrical surface and an outer contour coinciding with the outer cylindrical surface. The primary coil, shield coil , and coil jumps cooperatively define a current path that passes across the current-sharing surface between the inner and outer contours a plurality of times.

According to another aspect, a method is provided for producing a magnetic field gradient in a magnet bore of a magnetic resonance imaging apparatus. An electrical current is circulated through a primary coil that defines an inner cylindrical surface. The electrical current is circulated through a shield coil that defines an outer cylindrical surface coaxially aligned with the inner cylindrical surface and having a larger cylindrical radius than the inner cylindrical surface. The electrical current is communicated between the primary and shield coils via a plurality of non-planar coil jumps a plurality of times.

According to yet another aspect, a method is provided for designing a gradient coil for a magnetic resonance imaging apparatus. Current densities are computed on coaxial inner and outer cylindrical surfaces using constraints on the stored energy and gradient field linearity and uniformity. The computed current densities are generally non-zero at non-coplanar boundary contours that define coil edges. Primary coil turns, shield coil turns, and coil jumps are selected to approximate the computed current densities on the inner and outer cylindrical surfaces.

One advantage of designing the gradient coil with shared turns on the primary and shield coil is that it allows shorter shielded gradient coil designs.

Another advantage resides in reduced magnetic field gradient distortion due to eddy currents in the cold shield or other conductive elements of the magnetic resonance imaging scanner.

Another advantage resides in reduced current winding densities at the extremities of the gradient coil.

Yet another advantage resides in reduced I^2R heating, particularly in regions of high winding density.

Numerous additional advantages and benefits will become apparent to those of ordinary skill in the art upon reading the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 shows an exemplary magnetic resonance imaging apparatus, in partial cross-section, and auxiliary components for performing magnetic resonance imaging.

FIGURE 2 shows an enlarged cross-sectional view of the magnetic resonance imaging apparatus which shows a flared arrangement of primary and shield gradient coils and a current-sharing surface for passing current back and forth between the primary and shield gradient coils.

FIGURE 3 diagrammatically shows a sectional view of the geometrical arrangement of the primary and shield gradient coils of FIGURE 2, with a suitable dimensional nomenclature superimposed.

FIGURE 4 diagrammatically shows a perspective view of the geometrical arrangement of the primary and shield gradient coils.

FIGURE 5 shows an unfolded half-quadrant layout of the X-gradient primary and shield gradient coils and the interconnecting coil jumps.

FIGURE 6 shows exemplary isolated primary and shield coil turns of the X-gradient coil of FIGURE 5.

FIGURE 7 shows exemplary communicating primary and shield coil turns of the X-gradient coil of FIGURE 5.

FIGURE 8A shows a plot of gradient coil system energy versus the z-component of the current density at the edge of the primary coil for an exemplary transverse gradient coil design which has G_x = 30mT/m and the eddy current effect is - 0.22%.

FIGURE 8B shows a plot of gradient coil system energy versus residual eddy current effect for an exemplary transverse gradient coil design which has G_x=30 mT/m and $J_{zp,\ edge}$=17 kA/m.

FIGURE 9 shows a plot of the z-component of the current density for the primary and shield coils layout shown in FIGURE 5.

FIGURE 10 shows a plot of X-gradient non-uniformity at a radius of 0.001 meters for the primary and shield coils layout shown in FIGURE 5.

FIGURE 11 shows a plot of X-gradient non-linearity at z=0 meters as a function of radial position for the primary and shield coils layout shown in FIGURE 5.

FIGURE 12 shows a plot of residual eddy current distribution as a function of axial position Z produced by the coil layout shown in FIGURE 5.

FIGURE 13 shows a plot comparing eddy current effect as a function of axial position Z for the continuous current of FIGURE 9 and the discretized coils of FIGURE 5.

FIGURE 14 shows an unfolded half-quadrant layout of a coil **P2** formed by selecting fourteen turns on the primary coil of FIGURE 5 that do have jumps.

FIGURE 15 shows an unfolded half-quadrant layout of a coil **P1** formed by disconnecting fourteen isolated primary coil turns of the primary gradient coil **P2** of FIGURE 14.

FIGURE 16 shows an unfolded half-quadrant layout of a second shield coil **S2** that operates in conjunction with the coil **P1** to define a second field of view.

FIGURE 17 shows a plot of X-gradient non-uniformity for the two discrete fields of view of the gradient coil illustrated in FIGURES 5 and 14-16.

FIGURE 18 shows a plot of X-gradient non-linearity for the two discrete fields of view of the gradient coil illustrated in FIGURES 5 and 14-16.

FIGURE 19 shows an unfolded half-quadrant layout of a second shield coil **S2'** that operates in conjunction with the coils of FIGURES 5, 14, and 15 to define a discretely variable gradient coil with three fields of view.

FIGURE 20 shows two gradient coils driven in parallel, with nomenclature specified for computing a slew rate for the parallel-combined coils.

FIGURE 21 shows a suitable configuration of two primary coils located on a single surface and two shield coils designed as described herein that provide a continuously variable field of view.

FIGURE 22 shows a plot of the z-component of the current density for primary and shield coils providing a 32cm DSV field of view.

FIGURE 23 shows a plot of the z-component of the current density for primary and shield coils of a correction or shim coil that cooperates with the 32cm DSV coil of FIGURE 22 to produce a continuously variable field of view.

FIGURE 24 shows an unfolded half-quadrant layout of the primary and shield gradient coils and the interconnecting coil jumps of the discretized current densities of the 32cm DSV coil of FIGURE 22.

FIGURE 25 shows an unfolded half-quadrant layout of the primary gradient coil of the correction coil.

FIGURE 26 shows an unfolded half-quadrant layout of the shield gradient coil of the correction coil.

With reference to FIGURE 1, a magnetic resonance imaging scanner **10** includes a cylindrical main magnet **12**, which is preferably superconducting and cryoshielded. The main magnet **12** defines a magnet bore **14** inside of which a patient or other imaging subject is placed for imaging. The main magnet **12** produces a spatially and temporally constant and uniform main magnetic field oriented along a longitudinal axis of the bore **14**. Instead of a superconducting magnet, a non-superconducting magnet can be used. Moreover, a vertical magnet, an open magnet, or other type of main magnet can be employed instead of the illustrated horizontal cylindrical main magnet **12**. In one preferred embodiment, the main magnet **12** is a short-bore magnet.

Magnetic field gradient coils include a primary gradient coil **16** and a shield gradient coil **18** that cooperatively produce magnetic field gradients in the bore **14** for spatially encoding magnetic resonance signals, for producing magnetization-spoiling field gradients, or the like. Preferably, the magnetic field gradient coils **16, 18** include coils configured to produce magnetic field gradients in three orthogonal directions including transverse x- and y-directions. In addition to the shield coil **18**, a cold shield **20** provides a high conductivity eddy current surface for residual gradient fields thus protecting the magnet coils still further away. In

a suitable embodiment, the cold shield 20 is integrated into a housing of the main magnet 12.

A whole body radio frequency coil assembly 22 generates radio frequency pulses for exciting magnetic resonances. The radio frequency coil assembly 22 also serves to detect magnetic resonance signals. Optionally, additional local radio frequency coils or phased radio frequency coil arrays (not shown) are included for exciting and/or detecting magnetic resonances at localized areas in the bore 14.

Gradient pulse amplifiers 30 deliver controlled electrical currents to the magnetic field gradient coils 16, 18 to produce selected magnetic field gradients. A radio frequency transmitter 34, preferably digital, applies radio frequency pulses or pulse packets to the radio frequency coil assembly 22 to generate selected magnetic resonance excitations. A radio frequency receiver 36 also coupled to the radio frequency coil assembly 22 receives magnetic resonance signals. If more than one radio frequency coil is provided (such as a local coil or phased coil array), then different coils are optionally used for the magnetic resonance excitation and detection operations.

To acquire magnetic resonance imaging data of a subject, the subject is placed inside the magnet bore 14, preferably at or near an isocenter of the main magnetic field. A sequence controller 40 communicates with the gradient amplifiers 30 and the radio frequency transmitter 34 to produce selected transient or steady state magnetic resonance configurations in the subject, to spatially encode such magnetic resonances, to selectively spoil magnetic resonances, or otherwise generate selected magnetic resonance signals characteristic of the subject. The generated magnetic resonance signals are detected by the radio frequency receiver 36, and stored in a k-space memory 42. The imaging data is reconstructed by a reconstruction processor 44 to produce an image representation that is stored in an image memory 46. In

one suitable embodiment the reconstruction processor **44** performs an inverse Fourier transform reconstruction.

The resultant image representation is processed by a video processor **48** and displayed on a user interface **50**, which

5   is preferably a personal computer, workstation, or other type of computer. Rather than producing a video image, the image representation can be processed by a printer driver and printed, transmitted over a computer network or the Internet, or the like. Preferably, the user interface **50** also allows a

10   radiologist or other operator to communicate with the magnetic resonance sequence controller **40** to select magnetic resonance imaging sequences, modify imaging sequences, execute imaging sequences, and so forth.

With reference to FIGURE 2-4, the magnet **12** of the

15   magnetic resonance imaging scanner **10** is preferably a short-bore magnet defining a cylindrical magnet bore **14**. The primary and shield gradient coils **16**, **18** coincide with and define axially concentric cylindrical surfaces **60**, **62**, respectively. The inner and outer concentric cylindrical

20   surfaces **60**, **62** have radii R_p, R_s, respectively. The shield gradient coil **18** extends axially a half-length L_s along the outer cylindrical surface **62**, while the primary gradient coil **16** extends axially a half-length L_p along the inner cylindrical surface **60**. The cold shield **20** has a length $2L_{cs}$. Preferably,

25   the gradient coils **16**, **18** and the cold shield **20** are bilaterally symmetric along the axial direction, and L_s, L_p, L_{cs} designate half-lengths.

To provide reduced length, increased openness, and improved shielding, the axial half-length L_s of the shield

30   gradient coil **18** is preferably greater than the axial half-length L_p of the primary gradient coil **16**. The two gradient coils **16**, **18** are connected along a non-planar current-sharing surface **64** that extends between an inner contour **66** coinciding

with the inner cylindrical surface 60, and an outer contour 68 coinciding with the outer cylindrical surface 62. In a preferred embodiment, the non-planar current-sharing surface corresponds to a curved surface of a frustum of a cone, where

5   the cone has an angle α respective to an axis of the axially concentric cylindrical surfaces 60, 62. The angle α corresponds to an arctangent of a ratio of a difference between the cylindrical surface radii R_p, R_s and a difference between the primary and secondary or shield gradient coil half-lengths L_p,

10   L_s. However, the non-planar current-sharing surface can also have a parabolic, piece-wise conic, or other shape.

        With continuing reference to FIGURES 2-4 and with further reference to FIGURE 5, the primary gradient coil 16 includes a fingerprint-like pattern of conductive windings or

15   current paths coinciding with the inner cylindrical surface 60, while the shield gradient coil 18 includes a fingerprint-like pattern of conductive windings or current paths coinciding with the outer cylindrical surface 62.

        With continuing reference to FIGURES 2-5 and with

20   further reference to FIGURES 6 and 7, the primary gradient coil 16 includes isolated primary coil turns 70 that connect with other primary gradient coil turns on the surface 60. The primary gradient coil 16 also includes communicating primary coil turns 72 that each connect with at least one coil jump 74

25   that coincides with the current-sharing surface 64. Similarly, the shield gradient coil 18 includes isolated shield coil turns 80 that connect with other shield coil turns on the surface 62, as well as communicating shield coil turns 84 that each connect with at least one coil jump 74.

30   As shown in FIGURE 6, each isolated primary or shield coil turn 70, 80 defines a current loop on the cylindrical surface 60, 62, respectively. As shown in FIGURE 7, the

communicating primary and shield coil turns **72**, **82** and two coil jumps **74** define a current loop that passes back and forth across the current-sharing surface **64** via the two coil jumps **74**.

5   Those skilled in the art will recognize that the gradient coils **16**, **18** have substantial advantages over past coils, especially for short-magnet designs. By connecting the primary coil **16** and secondary or shield coil **18** with a plurality of coil jumps **74**, high coil turn densities near the
10   coil edges are reduced. Moreover, by axially flaring the shield coil **18** relative to the primary coil **16** improved shielding is obtained versus a design using primary and shield coils of equal lengths. The axial flaring of the shield coil **18** is accommodated by the non-planar current-sharing surface **64** to
15   permit a combination of a flared shield and multiple coil jumps.

With returning reference to FIGURE 3, a suitable method for designing the gradient coils **16**, **18** uses the following parameters. The angle α is called a flare angle. The
20   axial coil half-lengths L_p, L_s, and the cold shield half-length L_{cs} are shown and were discussed previously. Preferably, $L_p < L_s < L_{cs}$, with L_{cs} substantially larger than L_s. The primary coil **16** coincides with and defines the inner cylindrical surface **60** which has a radius R_p. The shield coil **18** coincides with and
25   defines the outer cylindrical surface **62** which has a radius R_s. The cold shield **20** is preferably cylindrical with a radius R_{cs}, and is preferably coaxial with the cylindrical surfaces **60**, **62**. For a preferred embodiment, $R_p < R_s < R_{cs}$.

The gradient coil design goals include producing: (i)
30   given gradient strength G_X or G_Y at the isocenter of the magnet bore **14**; (ii) high slew rate; (iii) good quality gradient magnetic field characteristics, such as linearity and

uniformity, within a given diameter spherical volume (DSV); and (iv) good shielding. It is recognized that leakage of the magnetic field into the conductive cold shield 20 will be present. This leakage is responsible for the residual eddy
5   currents induced in the cold shield 20 when the gradient coil 16, 18 is operated. These residual eddy currents can affect the quality of the gradient field inside the DSV and are characterized by the residual eddy current effect, which is defined as follows:
10

$$ed\_ef(r)|_{DSV} = \frac{B_z^{eddy\_current}(r)}{B_z^{Grad}(r)}|_{DSV} * 100\% \tag{1}$$

where the symbol $|_{DSV}$ indicates that the residual eddy current effect is evaluated at the surface of the DSV. One skilled in
15   the art knows that if the above characteristic is reasonably constant as a function of spatial position, r, then the residual eddy current effect can be substantially corrected with gradient pre-emphasis. Thus, the absolute level of eddy current magnitude, although generally desired or preferred to
20   be as small as possible, is not necessarily the most important aspect.

In designing a self-shielded gradient coil, which from the beginning has finite lengths of the primary and shield coils, shielding conditions for the normal component of the
25   total magnetic field $B_r(r)$ on the surface of the shield coil are typically imposed according to:

$$B_\rho(r)|_{\rho=R_s} = 0$$

$$\varepsilon(k) = F_s(k) + R(k)F_p(k) \rightarrow 0, \quad R(k) = \frac{R_p I_1'(kR_p)}{R_s I_1'(kR_s)} \tag{2}$$

30

$$F_{p,s}(k) = \int_{-L_{p,s}}^{L_{p,s}} f_\varphi^{(p,s)}(z)\cos(kz)dz$$

where $f_\varphi^{(p,s)}(z)$ is the φ-component of the current density on the primary (p) or shield (s) coil, $R_{p,s}$, $L_{p,s}$ are the radii and half-length of the primary (p) or shield (s) coil, respectively, and $I_1'(kR)$ is a derivative of a Bessel function of the first kind $I_1(kR)$. Equation (2) holds for any k, and is substantially restrictive. The shielding error function $\varepsilon(k)$ is a measure of how well the gradient coil is shielded. To design a well-shielded gradient coil Equation (2) leads to high current density on the primary coil with a negative lobe near its edge, leading therefore to high inductance.

If the residual eddy current effect is non-zero it should have small variation over the imaging volume to be correctable. This means, that the variation of the residual eddy current effect should be small, even if the residual eddy current effect is about, say, 10%. Therefore, the coil is designed to satisfy the conditions that there is no high current density near the ends of the coils and the residual eddy current effect is correctable.

The gradient coil design includes the following process operations: (i) allowing the current to flow off the end of the primary coil **16** to the shield coil **18** along the conical or other non-planar current-sharing surface **64** disposed therebetween; (ii) the cold shield **20** is included in the coil design; and (iii) the residual eddy current effect is considered as a variable in the design together with gradient field quality characteristics. The latter will be introduced as point constraints.

In the following, an exemplary X-gradient coil design is described. Those skilled in the art can readily adapt the exemplary X-gradient coil design to the designing of a Y-gradient coil. The current distribution on the X-gradient coil in terms of cylindrical coordinates has the following form:

$$\mathbf{J}(\mathbf{r}) = \mathbf{e}_\rho J_\rho(\mathbf{r}) + \mathbf{e}_\varphi J_\varphi(\mathbf{r}) + \mathbf{e}_z J_z(\mathbf{r})$$

$$J_\rho(\mathbf{r}) = J^{(\rho)}(\rho)\{\delta(z - Z(\rho)) + \delta(z + Z(\rho))\}\Theta(\rho - R_p)\Theta(R_s - \rho)\sin(\varphi)$$

$$J_\varphi(\mathbf{r}) = \left\{ f_\varphi^{(p)}(z)\delta(\rho - R_p)\Theta(z + L_p)\Theta(L_p - z) + f_\varphi^{(s)}(z)\delta(\rho - R_s)\Theta(z + L_s)\Theta(L_s - z) \right\}\cos(\varphi)$$

$$J_z(\mathbf{r}) = \left\{ f_z^{(p)}(z)\delta(\rho - R_p)\Theta(z + L_p)\Theta(L_p - z) + f_z^{(s)}(z)\delta(\rho - R_s)\Theta(z + L_s)\Theta(L_s - z) \right\}\sin(\varphi) +$$

$$J^{(z)}(\rho)\{\delta(z - Z(\rho)) - \delta(z + Z(\rho))\}\Theta(\rho - R_p)\Theta(R_s - \rho)\sin(\varphi)$$

$$Z(\rho) = L_p + (\rho - R_p)\cot(\vartheta), \quad \cot(\vartheta) = \frac{L_s - L_p}{R_s - R_p}$$

$$(3)$$

The continuity equation $\nabla \cdot \mathbf{J}(\mathbf{r}) = 0$ applied to the current $\mathbf{J}(\mathbf{r})$
given in Equation (3) above leads to the following equations:

$$R_p f_z^{(p)'}(z) = f_\varphi^{(p)}(z), \quad R_s f_z^{(s)'}(z) = f_\varphi^{(s)}(z),$$

$$\frac{\partial(\rho J^{(\rho)}(\rho))}{\partial \rho} = 0 \rightarrow J^{(\rho)}(\rho) = \frac{C}{\rho},$$

$$J^{(\rho)}(R_p) = f_z^{(p)}(L_p), \quad J^{(\rho)}(R_s) = -f_z^{(s)}(L_s), \quad (4)$$

$$J^{(z)}(\rho) = J^{(\rho)}(\rho)\cot(\vartheta),$$

$$C = R_p f_z^{(p)}(L_p) = -R_s f_z^{(s)}(L_p)$$

where the functions $f_z^{p,s}(z)$ are suitably represented as Fourier
series according to:

$$f_z^{(p)}(z) = \sum_{n=1} a_n^{(p)} \sin(\frac{\pi n}{2L_p} z), \quad f_z^{(s)}(z) = \sum_{n=1} a_n^{(s)} \sin(\frac{\pi n}{2L_s} z) \quad (5)$$

with the coefficients $a_n^{(p)}$, $a_n^{(s)}$ determined through extremization
of the following functional:

$$W = E - \sum_i (B_z^{coil}(\mathbf{r}_i) - B_i)\lambda_i - \sum_j (B_z^{CS}(\mathbf{r}_j) - C_j B_z^{coil}(\mathbf{r}_j))\Lambda_j -$$

$$(f_z^p(L_p) - A_p)\Lambda_p - (f_z^s(L_s) + \frac{R_p}{R_s}A_p)\Lambda_s \quad (6)$$

where: E represents total energy stored in the magnetic fields of the gradient coil **16**, **18** and the cold shield **20**; $B_z^{coil}(\mathbf{r}_i)$ is the z-component of the coil magnetic field at a set of points $\mathbf{r}_i$ inside the DSV where the field has predetermined values B_i;

$B_z^{CS}(\mathbf{r}_j)$ is the z-component of the magnetic field produced by the cold shield **20** at a set of points $\mathbf{r}_j$ on the surface of the DSV; $B_z^{coil}(\mathbf{r}_j)$ is the z-component of the coil's magnetic field at the same set of points; and C_j is a set of numbers that govern the residual eddy current effect. Finally, λ_i and Λ_j are the corresponding Lagrange multipliers. The quantity A_p is a desired value of the z-component of the current density on the primary coil at its edge, and the quantity $-\dfrac{R_p}{R_s}A_p$ is the value of the z-component of the current density at the edge of the shield coil. The continuity conditions are represented by the last two terms in Equation (6) and Λ_p, Λ_s are the corresponding Lagrange multipliers for the current continuity.

The quantities A_p and C_j are not variables and can be chosen arbitrarily. In deriving the Equation (6), we have assumed that the normal component of the total magnetic field vanishes on the surface of the magnet cold shield **20**, which has radius R_{CS}, which is assumed much longer than the length of the gradient set. This gives the following equation for the cold shield residual eddy current:

$$f_\varphi^{CS}(z) = \frac{1}{\pi} \int_0^\infty F_\varphi^{CS}(k)\cos(kz)\,dk$$

$$F_\varphi^{CS}(k) = -R(k,R_p,R_{CS})F_\varphi^P(k) - R(k,R_s,R_{CS})F_\varphi^s(k)$$

$$-2\frac{R_p f_z^P(L_p)}{R_{CS}}\int_{R_p}^{R_s} \frac{I_1(k\rho)}{I_1'(kR_{CS})}\cos(kZ(\rho))\frac{d\rho}{\rho}, \tag{7}$$

$$R(k,R,R_{CS}) = \frac{R I_1'(kR)}{R_{CS} I_1'(kR_{CS})}$$

where the Fourier transforms $F_{p,s}(k)$ of the primary and the shield current distributions are given in Equation (2). Variation of the functional W of Equation (6) with respect to a_n^p, a_n^s determines the solution in terms of continuous current distributions.

Optimization of the functional given in Equation (6) with respect to $a_n^{(p)}$ and $a_n^{(s)}$ determines a suitable solution by adjusting the value of the current density at the edge of the primary coil. After a solution is found the continuous current distributions on primary coil, shield coils and the interconnecting surface are discretized such that each loop on the primary coil carries the same current I, and each loop on the shield coil carries opposite current. The discretized coil is tested for its performance: gradient strength at isocenter, linearity and uniformity of the gradient strength over the DSV, and slew rate and residual eddy current effect.

The continuous current distributions are discretized and approximated by coils 70, 72, 74, 80, 82 carrying current along a current path. A suitable fingerprint pattern of the primary and shield coils 16, 18 and coil jumps 74 determined by the forgoing process is shown in FIGURE 5. The left and right half of the coil are the primary and shield coils 16, 18 respectively joined by coil jumps 74 at fixed angular positions ϕ along the current-sharing surface 64 that connects the concentric inner and outer cylindrical surfaces 60, 62.

With continuing reference to FIGURE 5 and with further reference to FIGURES 6 and 7, the two kinds of current paths, namely the isolated primary and shield coil turns **70**, **80** exemplarily shown in FIGURE 6 and the communicating primary and shield coil turn **72**, **82** shown in FIGURE 7 are generated. The isolated current loops **70**, **80** reside only on the primary or shield coil **16**, **18**, that is, only on one of the two cylindrical surfaces **60**, **62**. The communicating current paths **72**, **82** define current loops that reside on both the primary and shield coils **16**, **18**, that is, on both of the two cylindrical surfaces **60**, **62**, with coil jumps **74** defining current jumps or interconnections between them.

The B_z field from all of these paths is calculated to determine residual eddy currents in the cold shield **20**, which can be compared to the continuous current residual eddy current effects on the DSV. Each isolated loop **70**, **80** resides on either the primary coil **16** or shield coil **18** and is closed on itself. Examples of these loops are shown in FIGURE 6, which shows an isolated primary loop **70** on the inner cylindrical surface **60** and an isolated shield coil loop **80** located in the first quadrant, for example. Each loop carries a current I. The current on the isolated primary coil loop **70** flows clockwise, while the current on the shield coil loop **80** flows counterclockwise. Exemplary communicating primary and shield loops **72**, **82** defining a current loop passing back and forth across the non-planar current sharing surface **64** is shown in FIGURE 7.

A suitable process for calculating the magnetic field and associated residual eddy current in the magnet cold shield **20** from the discretized coil **16**, **18** is the path-integral approach. The coil is discretized, so an equation describing each loop is known, i.e. the equations $\varphi = f_p(z)$, $\varphi = f_s(z)$. For the isolated loops shown in FIGUER 6, the conditions

$f_p(p1) = f_p(p2) = 0, \quad f_s(s1) = f_s(s2) = 0$ apply. For the communicating loops shown in FIGURE 7, different conditions $f_p(p1) = f_s(s1) = 0, \quad f_p(L_p) = \varphi_f, \quad f_s(L_s) = \varphi_f$ apply, where φ_f is the angle at which the current-sharing coil jump occurs. Rather than the parameters p_1, p_2, s_1, s_2, the description henceforth uses z_i and z_f.

The current distribution produced by the communicating loops **72**, **82** shown in FIGURE 7 is given by:

$$\mathbf{J(r)} = \mathbf{e}_\rho J_\rho(\mathbf{r}) + \mathbf{e}_\varphi J_\varphi(\mathbf{r}) + \mathbf{e}_z J_z(\mathbf{r})$$

$$J_\rho(\mathbf{r}) = J^\rho(\rho)\delta(z - Z(\rho))\Theta(\rho - R_p)\Theta(R_s - \rho)\{\delta(\varphi - \varphi_f) - \delta(\varphi + \varphi_f)\},$$

$$J_\varphi(r) = Q_p R_p f_p'(z)\{\delta(\varphi - f_p(z)) + \delta(\varphi + f_p(z))\}\delta(\rho - R_p)\Theta(z_f^p - z)\Theta(z - z_i^p)$$

$$+ Q_s R_s f_s'(z)\{\delta(\varphi - f_s(z)) + \delta(\varphi + f_s(z))\}\delta(\rho - R_s)\Theta(z_f^s - z)\Theta(z - z_i^s), \qquad (8)$$

$$J_z(\mathbf{r}) = B_p\{\delta(\varphi - f_p(z)) - \delta(\varphi + f_p(z))\}\delta(\rho - R_p)\Theta(z_f^p - z)\Theta(z - z_i^p)$$

$$+ B_s\{\delta(\varphi - f_s(z)) - \delta(\varphi + f_s(z))\}\delta(\rho - R_s)\Theta(z_f^s - z)\Theta(z - z_i^s)$$

$$+ J^z(\rho)\delta(z - Z(\rho))\Theta(\rho - R_p)\Theta(R_s - \rho)\{\delta(\varphi - \varphi_f) - \delta(\varphi + \varphi_f)\}$$

where in Equation (8) Q_p, B_p, Q_s, B_s are unknown constants and $J^\rho(\rho), J^z(\rho)$ are unknown functions to be determined from the continuity equation $\nabla \cdot \mathbf{J(r)} = 0$. Thus,

$$Q_p = B_p = \frac{I}{R_p}, \qquad Q_s = B_s = -\frac{I}{R_s},$$

$$J^z(\rho) = J^\rho(\rho)\cot(\vartheta), \qquad J^\rho(\rho) = \frac{I}{\rho} \qquad (9).$$

This allows expressions for all components of the vector potentials, and therefore for magnetic field and residual eddy current, to be found. For example, the expression for the z-component of the magnetic field produced by a loop, combined from all four quadrants, is given by:

$$B_z(\mathbf{r}) = B_z^p(\mathbf{r}) + B_z^s(\mathbf{r}) + B_z^{CJ}(\mathbf{r}),$$

$$B_z^p(\mathbf{r}) = -\frac{8\mu_o I}{\pi^2} \sum_{n=1}^{\infty} \cos((2n-1)\varphi) \int_0^{\infty} dk \cos(kz)(kR_p) \Im_{2n-1}^p(k) \{\Theta(R_p - \rho)I_{2n-1}(k\rho)K_{2n-1}'(kR_p)$$

$$\Theta(\rho - R_p)K_{2n-1}(k\rho)I_{2n-1}'(kR_p)\},$$

$$B_z^s(\mathbf{r}) = \frac{8\mu_o I}{\pi^2} \sum_{n=1}^{\infty} \cos((2n-1)\varphi) \int_0^{\infty} dk \cos(kz)(kR_s) \Im_{2n-1}^s(k) \{\Theta(R_s - \rho)I_{2n-1}(k\rho)K_{2n-1}'(kR_s) \qquad (10)$$

$$\Theta(\rho - R_s)K_{2n-1}(k\rho)I_{2n-1}'(kR_s)\},$$

$$B_z^{CJ}(\mathbf{r}) = -\frac{8\mu_o I}{\pi^2} \sum_{n=1}^{\infty} (2n-1)\cos((2n-1)\varphi)\sin((2n-1)\varphi_f) \int_0^{\infty} dk \cos(kz) \int_{R_p}^{R_s} \frac{dx}{x} \cos(kZ(x))$$

$$\{\Theta(\rho - x)I_{2n-1}(k\rho)K_{2n-1}(kx) + \Theta(x - \rho)I_{2n-1}(kx)K_{2n-1}(k\rho)\}$$

where:

$$\Im_{2n-1}^p(k) = \int_{z_i^p}^{z_f^p} dz f_p'(\dot{z})\cos[(2n-1)f_p(z)]\cos(kz),$$

$$\qquad\qquad (11).$$

$$\Im_{2n-1}^s(k) = \int_{z_i^s}^{z_f^s} dz f_s'(z)\cos[(2n-1)f_s(z)]\cos(kz)$$

It will be recognized that all odd modes in $\cos((2n-1)\varphi)$ are present. These expressions hold for both isolated and communicating loops. For isolated coils 70, 80 that are closed on themselves, $z_i^{p,s}, z_f^{p,s}$ are the initial and final points of the primary (p) or shield (s) loop in the upper-half of the first quadrant. Communicating loops 72, 82 which connect with at least one coil jump 74 have $z_i^{p,s}$ as initial points on the primary (p) or shield (s) loop in the upper half of the first quadrant, and $z_f^{p,s} = L_{p,s}$. From Equation (2) the result for the z-component of the residual eddy current is:

$$f_z^{CS}(z,\varphi) = \sum_{n=1}^{\infty} f_{z,2n-1}^{CS}(z)\cos[(2n-1)\varphi],$$

$$f_{z,2n-1}^{CS}(z) = \frac{1}{\pi}\int_0^{\infty} F_{2n-1}^{CS}(k)\sin(kz)dz,$$

$$F_{2n-1}^{CS}(k) = -\frac{8I}{\pi}(\frac{1}{R_p}\Re(k,R_p,R_{CS})\aleph_{2n-1}^p(k) - \frac{1}{R_s}\Re(k,R_s,R_{CS})\aleph_{2n-1}^s(k) \qquad (12)$$

$$+\frac{\sin[(2n-1)\varphi_f]}{kR_{CS}}[\frac{R_{CS}}{R_p}\Re(k,R_p,R_{CS})\cos(kz_f^p) - \frac{R_{CS}}{R_s}\Re(k,R_s,R_{CS})\cos(kz_f^s)$$

$$+(2n-1)^2\int_{R_p}^{R_s}\frac{dx}{x}\cos(kZ(x))\frac{I_{2n-1}(kx)}{(kR_{CS})I_{2n-1}'(kR_{CS})}] \qquad)$$

where the following notations are introduced:

$$\Re(k,R,R_{CS}) = \left(\frac{R_p}{R_s}\right)^2 \frac{I_{2n-1}'(kR)}{I_{2n-1}'(kR_{CS})},$$

$$\aleph_{2n-1}^{p,s}(k) = \int_{z_f^{p,s}}^{z_f^{p,s}} dz\sin[(2n-1)f_{p,s}(z)]\sin(kz) \qquad (13).$$

The above approach can also be adapted to the design of a self-shielded axial gradient (Z-gradient) coil. In this case, it is sufficient to find the J_φ component of the current density on both the primary and the shield coils. This component does not necessarily vanish at the coil edges. In other words, the current continuity equation $\nabla \cdot \mathbf{J} = 0$ does not imply that the J_φ component of the current density should be a continuous function of z even at the edges of the coils. Therefore, the values of the current densities at the edges of the coils can be treated as free parameters during the design. Thus,

$$\mathbf{J}(\mathbf{r}) = \mathbf{e}_\varphi J_\varphi(\mathbf{r})$$

$$J_\varphi(\mathbf{r}) = \left\{ f_\varphi^{(p)}(z)\delta(\rho - R_p)\Theta(z + L_p)\Theta(L_p - z) + f_\varphi^{(s)}(z)\delta(\rho - R_s)\Theta(z + L_s)\Theta(L_s - z) \right\}$$

$$(14)$$

where the functions $f_\varphi^{p,s}(z)$ are suitably represented as a Fourier series:

$$f_\varphi^{(p)}(z) = \sum_{n=1} a_n^{(p)} \sin(\frac{\pi n}{2L_p}z), \qquad f_\varphi^{(s)}(z) = \sum_{n=1} a_n^{(s)} \sin(\frac{\pi n}{2L_s}z) \qquad (15)$$

with the coefficients $a_n^{(p)}$, $a_n^{(s)}$ being determined from extremization of the functional:

$$W = E - \sum_i (B_z^{coil}(\mathbf{r}_i) - B_i)\lambda_i - \sum_j (B_z^{CS}(\mathbf{r}_j) - C_j B_z^{coil}(\mathbf{r}_j))\Lambda_j -$$
$$(f_z^p(L_p) - A_p)\Lambda_p - (f_z^s(L_s) + A_s)\Lambda_s \qquad (16)$$

where: E is the total energy of the gradient coil and the cold shield; $B_z^{coil}(\mathbf{r}_i)$ is the z-component of the coil magnetic field at a set of points $\mathbf{r}_i$ inside the DSV where the field has predetermined values B_i; $B_z^{CS}(\mathbf{r}_j)$ is the z-component of the magnetic field produced by the cold shield eddy currents at a set of points $\mathbf{r}_j$ on the surface of the DSV; $B_z^{coil}(\mathbf{r}_j)$ is the z-component of the coil's magnetic field at the same set of points; and C_j is a set of numbers that govern the residual eddy current effect. Finally, λ_i and Λ_j are the corresponding Lagrange multipliers. The quantities A_p, A_s are the desired values of the φ-component of the current densities at the edges of the primary and shield coils, respectively. In Equation (16)

the shielding condition on the surface of the cold shield **20**, namely:

$$B_\rho(\mathbf{r})|_{\rho=R_{CS}} = 0 \tag{17}$$

has been incorporated. This leads to a continuous residual eddy current distribution given by:

$$f_\varphi^{CS}(z) = \frac{1}{\pi} \int_0^\infty F_{CS}(k)\sin(kz)dz$$

$$F_{CS}(k) = -Sh(k,R_p,R_{CS})F_p(k) - Sh(k,R_s,R_{CS})F_s(k) \tag{18}.$$

$$F_{p,s}(k) = \int_{-L_{p,s}}^{L_{p,s}} f_\varphi^{p,s}(z)\sin(kz)dz, \quad Sh(k,R,R_{CS}) = \frac{RI_1(kR)}{R_{CS}I_1(kR_{CS})}$$

Optimization of the functional given in Equation (16) with respect to $a_n^{(p)}$ and $a_n^{(s)}$ determines a suitable solution by adjusting the values of the current densities at the edge of the primary coil and the shield coil. After a solution is found the continuous current distributions on both primary and shield coils are discretized such that each loop on the primary coil carries the same current I, and each loop on the shield coil carries opposite current. The discretized coil is tested for its performance: gradient strength at isocenter, linearity and uniformity of the gradient strength over the DSV, slew rate, and residual eddy current effect.

An exemplary transverse gradient coil design is described. The exemplary coil is designed for a magnet bore having a length of 1.2 meters and a bore radius of 0.45 meters. Design dimensions of the exemplary transverse gradient coil are as follows: R_P = 0.34385m, L_P = 0.434 meters, R_S = 0.435224 meters, L_S = 0.555 meters. In all examples described herein the target eddy current effect was chosen to be -0.22%.

The coil is aligned such that the flare angle α shown
in FIGURE 3 is 36.9°. In designing the X-gradient coil the
field constraints shown in Table 1 were used.

5   Table 1.

ρ-position (m)	Φ-position	z-position (m)	B_z (Tesla)
0.001	0.000	0.000	2.7e-5
0.180	0.000	0.000	4.86528530650126e-3
0.001	0.000	0.200	2.069587125e-5

The first constraint corresponds to the gradient strength of G_X
= 27mT/m at the isocenter, the second constraint is assigned
for no-rollover of the z-component of the gradient magnetic
10   field, and the third constraint corresponds to -23% of non-
uniformity of the gradient strength at z = 0.2 meters. The
residual eddy current effect constraints were imposed at a set
of points, which are given in Table 2.

15   Table 2.

z-position (m)	ρ-position (m)
0.0128	0.2495
0.06304	0.2373
0.1296	0.1904
0.19904	0.0245

The radius of the cold shield 20 was chosen to be $R_{cs} = 0.475m$.
The coil jumps 74 between primary and shield coils 16, 18 at
the ends of the gradient assembly result in a significant
20   reduction in stored energy and a change of residual eddy
current effects. A study was done of total energy vs. the
current density at the edge of the primary coil (quantity A_p in
Equation 6) and the residual eddy current effect (quantity C_j,
the percent measurement of the residual eddy current effect, in
25   Equation 6).

FIGURE 8A shows the plot for the energy of the system, rescaled to the gradient strength of 30mT/m and corrected back to account for the loss of the gradient strength due to the residual eddy current effect at the isocenter of the

5   coil, as a function of the current density at the edge of the primary coil when the residual eddy current effect is equal to an exemplary -0.22%. FIGURE 8B, shows the plot for the energy of the system, rescaled to the gradient strength of 30mT/m and corrected back to account for the loss of the gradient strength

10   due to the residual eddy current effect at the isocenter of the coil, as a function of the eddy current effect. In FIGURE 8B the current density at the edge of the primary coil is equal to an exemplary 17.0kA/m. FIGURE 8A shows that the total energy at the gradient strength of G_x=30mT/m after accounting for the

15   residual eddy current effect at the isocenter of the coil, has a minimum at a certain value of the quantity A_p for a given value of the residual eddy current effect. This value is suitably adjusted such that when the current densities on the primary and shield coils 16, 18 are discretized, the numbers of

20   turns are integers.

FIGURE 9 shows the results for the continuous current distributions shown in the unfolded coil layout of FIGURE 5. The continuous current distributions shown in FIGURE 9 were discretized with 29 turns on the primary coil 16 and 19 turns

25   on the shield coil 18 per quadrant with 14 coil jumps 74 per half of each quadrant. Each closed loop carries current $I = 398.64A$ in order to produce gradient strength $G_X = 30.0$mT/m at isocenter. The current layout per half quadrant is shown in FIGURE 5. Henceforth, P and S denote the whole primary coil 16

30   and the whole shield coil 18, respectively, which together with the coil jumps 74 provide 50cm×40cm imaging volume.

The discretized current was used to calculate magnetic field quality characteristics. FIGURE 10 shows X-gradient field non-uniformity (taking the transverse gradient

35   coil as producing an X-gradient; of course, the transverse

gradient coil can also be suitably oriented to produce a
Y-gradient or other transverse gradient), while FIGURE 11 shows
X-gradient field non-linearity.

   FIGURE 12 shows the z-component of residual eddy
current produced by the X-gradient coil having the current
paths shown in FIGURE 5. The residual eddy current of FIGURE 12
and the discretized loops shown in FIGURE 5 were used to
calculate a residual eddy current effect over 50cm×40cm volume.
The comparison of this result with that obtained from the
continuous currents is shown in FIGURE 13. This figure shows
that the discretization procedure does not introduce
substantial error in terms of magnitude and its variation over
the volume.

   With reference to FIGURES 14 and 15, the transverse
gradient coil whose layout is shown in FIGURE 5 is readily
adapted to provide a discretely variable field of view. In a
suitable modification, fourteen isolated primary coils **70** near
the eye of the primary coil fingerprint are electrically
decoupled from the remainder to define an interconnected coil
shown in FIGURE 14 and designated as **P2** herein. As shown in
FIGURE 15, a remainder **P1** of the primary coil **16** remains
electrically connected with the shield coil **18**. For
convenience, the original coupled primary coil **16** is designated
as **P** herein. Hence, **P=P1+P2**. Similarly, the shield coil **18** is
also designated by **S** herein.

   With reference to FIGURE 16, a second shield coil **S2**
is designed to compensate for the fourteen electrically
disconnected loops comprising the primary coil **P2**. A radial
position of the second shield coil **S2** is 0.415224m. The current
layout on the second shield coil is shown in FIGURE 16. The
current on the second shield S2 is I=398.64A. Combination of
the coil shown in FIGURE 15 with the second shield coil shown
in FIGURE 16, where the current flows in the same direction as

on the primary coil, provides a reduced DSV of 30cm. The non-uniformity and non-linearity of the gradient strength of two modes gradient coils are shown in FIGURES 17 and 18, respectively. The main mode coil corresponding to the layout of FIGURE 5 provides 50cmX40cm imaging volume, while the coil of FIGURE 15 combined with the second shield **S2** shown in FIGURE 16 provides 30cm DSV.

If a second power supply is provided, the gradient coil **16, 18** can be further modified to provide three discrete fields of view. The second shield coil **S2** is replaced by an eight-turn shield coil **S2'** positioned at the same radial location. A base mode, which provides 50cmX40cm imaging volume, is generated by the gradient coil shown in FIGURE 5 driven at a current I.

A second mode, which provides 30cm DSV, is generated by the gradient coil shown in FIGURE 15 driven with a current I, combined with the second shield **S2** shown in FIGURE 19 driven with a current I/2. Hence, two power supplies (or a current divider) are used.

A third mode is generated by the gradient coil shown in FIGURE 15 operating concurrently with the inner fourteen loop coil **P2** of FIGURE 14. The current in the primary coil **P2** is reversed relative to the current in the primary coil **P1** of FIGURE 15. The second shield **S2** of FIGURE 19 is driven with a current -I. In this third mode, all coils are driven in series, and one power supply is used. This configuration provides 26cm DSV.

When two coils are driven in series, a slew rate of the series-combined coils is given by:

$$SR = S * \frac{V - IR}{L} \qquad (19)$$

where: S is a sensitivity of the coil: $S = \dfrac{G}{I}$, with G and I

being the gradient strength and the current, respectively; V is

a output voltage of the power supply; R is a resistance of the

coil including the cable resistance; and L is an inductance of

5   the coil including the cable and filters inductance.

With reference to FIGURE 20, when two coils are

driven in parallel, the slew rate of the combined coil can be

found by considering the coupling equations between two

electric circuits, given by:

10

$$L_1 \frac{dI_1}{dt} + R_1 I_1 + M \frac{dI_2}{dt} = V_1, \qquad L_2 \frac{dI_2}{dt} + R_2 I_2 + M \frac{dI_1}{dt} = V_2 \qquad (20)$$

where L_1, R_1, V_1 and L_2, R_2, V_2 are the inductance, resistance, and

output voltage of the first and the second circuits,

15   respectively, and M is the mutual inductance between these two

coils. Then the slew rate of the combined coil is given by:

$$SR = \frac{1}{\Delta} \{ (S_1 L_2 - S_2 M)(V_1 - R_1 I_1) + (S_2 L_1 - S_1 M)(V_2 - R_2 I_2) \}$$
$$\Delta = L_1 L_2 - M^2 \qquad (21)$$

20   where S_1, S_2 is the sensitivity of the first and second coils,

respectively.

Moreover, the gradient coils of FIGURE 5, including

the primary coils **16** and secondary or shield coils **18**, which

are also designated herein as **P** and **S**, respectively, are

25   readily modified to provide a continuous field of view.

Starting with the initial coil system **P+S**, which

provides the imaging volume with largest FoV, a variable FoV

system can be achieved in the following way: (1) electrically

disconnect several turns near the eye of the primary coil (this

defines the coil **P2**, for example as shown in FIGURE 14) and the remaining primary coil is **P1 = P - P2** (for example as shown in FIGURE 15). The coil **P1** includes communicating coil turns **72** that communicate with communicating coil turns **82** of the shield coil **18** by coil jumps **74** at the ends of the gradient. The positions of these interconnects are known and fixed. Optionally, the coil **P1** also has some isolated turns that are only on the inner cylindrical surface **60**.

A second shield **S1** is designed to conform with the following conditions: (i) the number of conical jumps on this coil and their angular and axial positions match those on the primary coil **P1**; and (ii) shield **S1** together with the primary coil **P1** form a well-shielded pair. The system **P1 + S1** provides a reduced DSV1 < DSV relative to the gradient coil **16, 18** of FIGURE 5.

A second shield coil **S2''** is designed for the coil **P2**. The second shield coil **S2''** together with the coil **P2** form a well shielded pair. The combination of **S1** and **S2''** is equivalent to the initial coil **S**. The original coil **P** is not used (it was an intermediate process operation in the design procedure). Rather, two well-shielded pairs of coils: **P1 + S1** and **P2 + S2''** are the final result of the design.

These coil sets can be used as to provide either a discretely selectable FoV as in the previous examples or a continuously variable FoV. For a discretely selectable FoV, the coil **(P1+P2)+(S1+S2'')** provides the initial imaging volume DSV. The coil **P1+S1** provides DSV1 < DSV. The coil **(P1-P2)+ (S1-S2'')** provides DSV2 < DSV1.

With reference to FIGURE 21, for a continuously variable FoV, the coil sets **(P1+S1)** and **(P2+S2'')** provide a continuously variable FoV when used in conjunction with two power supplies. In this arrangement, one coil set **(P1+S1)** is driven by a current **I** from a first power supply, while the coil

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set (P2+S2'') is driven by the current α*I from a second power

supply. The parameter α adjusts the size of the FoV.

With reference to FIGURE 22, another gradient coil

with a continuously variable field of view is described. In

5   this approach, a well-shielded coil is designed in accordance

with process operations described previously, including current

transfer between inner and outer cylindrical surfaces

corresponding to primary and shield gradient coils,

respectively, across a non-planar current-sharing surface.

10   FIGURE 22 shows a suitable continuous current density for such

a coil which produces a 32 cm DSV.

A correction or shim gradient coil is designed in

such a way that it produces zero gradient strength at an

isocenter of the coil and together with the 32cm DSV gradient

15   coil produces a 50cmx40cm DSV. By itself the correction coil is

well shielded.

The correction coil is suitably designed as follows:

a well-shielded gradient coil is designed, including a

non-planar current-sharing surface, that provides 50cmX40cm

20   imaging volume and has the same gradient strength at the

isocenter as that of the 32cm DSV coil. The value of the

current density at the edge of the primary coil is the same as

in the gradient coil that provides 32cm DSV. The difference

(subtraction) between the current densities (on primaries and

25   separately shield coils) of 50cmx40cm and 32cm DSV defines the

correction coil. The values of the current density at the edge

of the coils are adjusted in such a way that allows proper

discretization. An example of the current density on the

correction gradient coil is shown in FIGURE 23.

30   The current distributions of the 32 cm DSV gradient

coil are discretized to generate a current layout such as that

shown in FIGURE 24. Similarly, the correction or shim coil

current distributions are discretized to generate a current

layout such as the primary and shield shim coil current layouts shown in FIGURES 25 and 26, respectively.

Variation of the amount of current in the correction gradient coil allows continuous variation of the FoV. The driving coil interconnections of FIGURE 21 can be used in driving the 32cm FOV gradient coils of FIGURE 24 and the correction coils of FIGURES 25 and 26. In this approach the coils **P1** and **S1** correspond to the well-shielded coil set of FIGURE 24 that provides the 32cm FoV, and **P2** and **S2''** correspond to the well-shielded correction coil pair shown in FIGURES 25 and 26.

FIGURES 24-26 describe an arrangement in which the primary coil (FIGURE 24) produces a base field of view (32cm) that is continuously enlargeable by cooperative operation of the correction coils of FIGURES 25 and 26. Alternatively, a base coil can provide a large base field of view which is continuously reducible by cooperative operation of correction coils.

Moreover, although design of transverse X-gradient coils are described herein, those skilled in the art recognize that the design of a transverse Y-gradient coil is substantively similar to design of an X-gradient coil, differing by a rotation of the whole gradient assembly by 90°.

The gradient coil design procedures described herein are readily modified to accommodate other design aspects. For example, local forces on the gradient coil can be reduced by introducing an additional constraint that the net (thrust) force on the gradient coil be zero. This constraint incorporates information about the main magnet that the gradient coil will be used with. Reduction in the local forces on the gradient coil can reduce gradient tube deflection when the coil is operated.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and

alterations will occur to others upon reading and understanding
the preceding detailed description. It is intended that the
invention be construed as including all such modifications and
alterations insofar as they come within the scope of the
5   appended   claims   or   the   equivalents   thereof.